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ORIGIN OF MASSIVE SERPENTINE AND CHRYSOTILE-ASBESTOS, BLACK LAKE-THETFORD AREA, QUEBEC.

BY

R. P. D. GRAHAM.

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GENERAL GEOLOGY OF THE AREA.

The eastern townships of the Province of Quebec have for many years been the center of the world's asbestos (chrysotile) industry. The deposits occur within a discontinuous belt of basic igneous rocks, which are throughout their course altered, to a greater or lesser extent, to serpentine, for which reason they are generally referred to as the "*serpentine belt.*"

Up to the present time the main production of chrysotile has come from two separate centers along this belt, namely, Black Lake-Thetford and East Broughton. The mode of occurrence in these two areas is somewhat different; in the former, the material forms veins in which the fiber lies cross-wise, while in East Broughton it occurs almost entirely as "slip fiber" in which thin layers of fiber lie parallel to the rock fractures. In the following pages an attempt is made to account for the formation of the massive serpentine and of the chrysotile in the Black Lake-Thetford area, and also to show the relation in which the two stand to one another.

For detailed information concerning the geology of the serpentine belt we are indebted mainly to Mr. J. A. Dresser, whose report[1] appeared in 1913, and the writer wishes to acknowledge the free use he has made, wherever necessary, of the data presented in this report.

The general geology of the area, as interpreted by Dresser, may be summarized as follows:

The serpentine belt consists of a series of igneous rocks of basic composition, which are intrusive through sedimentary strata of Palæozoic age. In the Black Lake-Thetford area, the latter are mainly upper Cambrian and lower Ordovician; further south, Silurian and early Devonian strata are also thought to be intruded, while to the north, in Broughton township, the igneous rocks appear to be older, though even here they were probably not intruded before late Cambrian time. Thus the rocks of the belt are principally post-Ordovician in age, and possibly they were intruded in Devonian time.

These igneous rocks include peridotite, pyroxenite, gabbro, diabase, porphyrite and hornblende granite, the latter sometimes passing into aplite; and the various types are all regarded as having differentiated from a single parent magma. The granite has usually been injected a little later than the other members of the series, and therefore in many places forms dykes and sills or intrusive sheets.

In the Black Lake-Thetford area, the igneous complex may be regarded as a batholith, exposed as a series of isolated stocks, and in these the different rock varieties are arranged in order of decreasing density and basicity from the center outward. Thus, as a result of truncation, their outcrop shows a central zone of peridotite, passing into the more acid rock types toward the margin. The serpentine gives its name to the belt owing to its economic importance, although actually it is the least abundant of the principal rocks of the series, occupying only small areas where the peridotite, and possibly also the pyroxenite, have been altered to serpentine.

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[1] Preliminary Report on the Serpentine and Associated Rocks of Southern Quebec, by John A. Dresser, Geological Survey, Can., Memoir 22, 1913.

MODE OF OCCURRENCE OF THE MASSIVE SERPENTINE AND CHRYSOTILE.

Detailed descriptions of the mode of occurrence of the massive serpentine and chrysotile-asbestos in the area may be found by referring to the report of Cirkel,[2] and, more especially, to that of Dresser. Some of the outstanding features may be briefly tabulated here. The most important points which have a direct bearing upon the genesis are as follows:

The massive serpentine occurs within the peridotite masses in the form of zones or bands whose boundaries against the peridotite are fairly well defined and are roughly parallel to one another, *i. e.*, they resemble dykes in outline and vary in dip from vertical to horizontal.

The more prominent bands fall into roughly rectilinear sets, which follow the same directions as the main system of joints in the peridotite. Others, which are in general narrower and more irregular in their course, intersect these and one another at all angles, so that in some places the peridotite presents a remarkably intricate network of such serpentine bands. Of these minor bands, Dresser believes some follow strain fractures due to regional compression, and others cracks caused by exfoliation.

✓ The central part of these massive serpentine bands is usually occupied by the fibrous variety, chrysotile; this also is dyke like in shape, *i. e.*, its boundaries against the massive serpentine are roughly parallel to one another and are rather sharply defined.

✓ There appears to be a fairly constant relation between the total width of any massive serpentine band and of the chrysotile vein which it encloses. Attention was first called to this feature by Dresser, who, from a number of measurements (49), found that the entire massive serpentine band is about 6.6 times as wide as the asbestos vein within it.

---

[2] "Chrysotile-Asbestos, its Occurrence, Exploitation, Milling and Uses," by Fritz Cirkel. Mines Branch, Dept. of Mines, Ottawa, Canada, 1910.

The chrysotile fibers are arranged parallel to one another, and extend transversely across the vein. Usually the fibers are not continuous across the vein, especially in the wider ones, but there is a parting, or sometimes more than one, at or near the center, which is occupied by a film of granular iron ore, usually magnetite.

There is an almost complete absence of carbonates, or of quartz, in the form of veins or otherwise, from the serpentine and associated rocks of the area.

Lastly, granite is frequently found in the vicinity of good asbestos deposits, or, an accumulation of asbestos veins (and therefore also of serpentine bands) can very frequently be noticed in approaching the granite dykes.

MODE OF ORIGIN OF THE MASSIVE SERPENTINE.

It is generally agreed that the massive serpentine has resulted from the alteration of the peridotite, and it is further believed that this metamorphism commenced along joint planes and other fractures, from which it proceeded outward in both directions. The main system of rectilinear joint planes is no doubt to be ascribed largely to the strains set up within the rock masses as they contracted on cooling, and along many of them dykes of granite were later injected. After a careful analysis of all the available field evidence, Dresser concludes that the magma from which the peridotite separated, underwent progressive differentiation until the last acid fraction had the composition of a granite, and he believes it is highly probable that the granite dykes are the visible expression of this final differentiate.

So far as the writer's observations go, these granite dykes are nowhere seen to intersect one another or to be cut by later igneous bodies, and it is probably safe to assert that, whatever their age, they are all contemporaneous and mark the latest phase of igneous activity in the area. Since Dresser cites one or two instances in the field where the granite occurs almost certainly as a direct differentiation product, and in the absence of any evidence to the contrary, the dykes also are here assumed to stand in that relation to the peridotite and therefore to be separated by no very great time interval from the intrusion and consolidation of the latter. On this view, the formation of the joint planes and the injection of the granite dykes were more or less contemporaneous, and the change from peridotite to serpentine is thus correlated with the period of granitic intrusions, or some time subsequent thereto.

The field relations of the peridotite and serpentine so clearly and completely support the hypothesis that the latter has been produced by the alteration of the former, that this view may well be considered as an established fact: but with regard to the processes by which the change has been brought about there is by no means such clear and definite evidence, consequently the opinions held by different investigators vary. A discussion of the question naturally falls under two heads, one dealing with the nature of the reagents necessary to produce the metamorphism and the other with their source. At the outset, however, it is necessary to have a knowledge of the approximate chemical composition of the olivine contained in the peridotite, and also of the serpentine.

COMPOSITION OF THE OLIVINE AND SERPENTINE.

No analyses of the olivine contained in the peridotite are available but two analyses of the rock itself (dunite type), made by M. F. Connor, are quoted in Dresser's Report. These are as follows.

The large percentage of water, liberated only on ignition, indicates the presence in considerable quantity of some mineral containing water of constitution, and it is probably safe to assume that this is mainly serpentine. Removing the latter in the form of the compound $H_4Mg_3Si_2O_9$, which represents nearly enough its composition, it is found that the amounts of magnesia and silica remaining are approximately in the ratio 2:1, there being only a slight excess of MgO over this proportion. This might suggest that the olivine present is a nearly pure forsterite

Analyses of the Peridote and Calculated Mineral Composition of the Rock.

	%	Mol. Ratio.	$2H_2O$, $3MgO$, $2SiO_2$.	$2MgO$, SiO_2.	FeO, Fe_2O_3.	Not Used.	%	Mol. Ratio.	$2H_2O$, $3MgO$, $2SiO_2$.	$2MgO$, SiO_2.	FeO, Fe_2O_3.	Not Used.
SiO_2	38.16	.636	.535	.101		—	38.24	.637	.540	.097		—
Al_2O_3	0.63	.006				.006	0.70	.007				.007
Fe_2O_3	3.32	.020			.020	—	3.50	.022			.022	—
FeO	4.76	.066			.020	.046	4.25	.066			.022	.048
MgO	41.84	1.046	.802	.202		.042	41.92	1.048	.810	.194		.044
CaO	0.68	.012				.012	0.68	.012				.012
$(K, Na)_2O$	0.20	—				—	0.20	—				—
$H_2O - 110°$	0.47	—				—	0.60	—				—
$H_2O + 110°$	9.63	.535	.535			—	9.76	.540	.540			—
	99.69						99.85					
No. of molecules			.2675	.101	.020	......	......	......	.270	.097	.022	
			×	×	×				×	×	×	
Mol. volume			107.021	43.179	44.515	......	......	......	107.021	43.179	44.515	
Relative volumes			28.628	0.4301	0.0890	......	......	......	28.896	0.4188	0.0979	
Per cent. by volume			84.50	12.87	2.63				84.83	12.29	2.88	
Mineral			Serpentine	Forsterite	Magnetite				Serpentine	Forsterite	Magnetite	

$(2MgO.SiO_2)$ [illegible] iron, and that the latter metal is present [illegible] nearly in the form of magnetite. The percentage [illegible] the rock by volume, calculated [illegible] above.

It should be added that the peridotite is not always so highly altered [illegible] and Dresser states that "the [illegible] a peridotite consisting of 80 per cent [illegible] per cent [illegible]"; but there is no reason for supposing that [illegible] differ materially from that shown in the [illegible].

Since magnetite is [illegible] present in the rock as disseminated [illegible], it is [illegible] certain that a portion of the ferrous [illegible] the serpentine molecule. Assuming, however, that [illegible] of the ferrous oxide shown in the above analyses were [illegible] in the olivine, replacing its equivalent of [illegible] would then contain Mg: Fe nearly in the ratio [illegible]. [illegible] composition [illegible] may thus be [illegible] which actually is never reached or even [illegible] approached.

The [illegible] of the olivine might be roughly compared in another way, by assuming that the ferrous oxide which is left [illegible] after [illegible] the amount required to form magnetite, enters into the composition of the various minerals of the rock proportionately to the total magnesia. This gives the ratio Mg: Fe [illegible], or about 23:1, corresponding to Mg_{23}-[illegible]. While [illegible] taken as indicating the limiting [illegible] in the other direction, it is probable that [illegible] far from representing the true state of affairs [illegible] never approaches so closely to the [illegible].

Since magnetite grains can [illegible] be seen scattered through the [illegible], it is reasonable to suppose that the [illegible] the analyses of these rocks is present [illegible] the necessary amount of ferrous oxide, in [illegible]. In the case of the first [illegible] the analysis [illegible] is almost identical with [illegible].

[illegible]

have 3.32 per cent. Fe_2O_3 united with 1.49 per cent. FeO to form $FeO \cdot Fe_2O_3$, leaving 3.27 per cent. FeO to be distributed between the serpentine and olivine.

The amount of ferrous oxide required for the serpentine may be arrived at by considering the analysis given in column (1) below: this was made by M. F. Connor, and is reproduced from Dresser's Report.

	[illegible]	[illegible]
SiO_2	40.08	39.62
TiO_2	None	- -
Al_2O_3	3.11	0.81
Fe_2O_3	1.13	†4.52
FeO	1.70	1.90
MgO	*37.00	39.73
CaO	0.20	Trace
K_2O	0.10	Not detd.
Na_2O		Not detd.
H_2O - 110°	1.35	0.43
H_2O + 110°	13.80	13.32
	98.46	100.33

* Probably low.

† Probably admixed magnetite.

The ferric oxide shown in the analysis (1.13 per cent.), assumed to be all combined in magnetite, will account for 0.51 per cent. FeO, so that the serpentine molecule itself contains 1.70 minus 0.51 or 1.19 per cent. FeO. The theoretical composition of such a serpentine, provided it conforms to the usual type ($H_4Mg_3Si_2O_9$), is as follows:

	[illegible]	[illegible]
SiO_2	43.25	.535
MgO	42.68	.790
FeO	1.10	.012
H_2O	12.98	.535

In the last column are given the molecular ratios, reduced to the basis H_2O = .535 so as to be directly comparable with those in the other table. As will be seen, the ratio Mg : Fe is about 65 : 1, and the serpentine has the composition $H_{88}Mg_{65}Fe_1Si_{44}O_{198}$.

Reasoning in this way then, the ferrous oxide found in the analysis of the peridotite is apportioned as follows:

[illegible]	[illegible]	Hence [illegible]

[illegible] (SiO) [illegible] 0.33 H₂O [illegible] 1.88 MgO [illegible] 2.02 [illegible] as the fo- [illegible].

[illegible] at this formula [illegible] open to criticism, as also the fact that [illegible] on the basis of a single anal- [illegible]. [illegible] of the olivine, and in a lesser degree of the serpentine [illegible] of some importance in consider- [illegible] at an approximate [illegible] Mg : Fe [illegible] in the olivine, [illegible] by the alteration [illegible].

[illegible] evidence on this [illegible] of the peri- [illegible] the order 5 : 1 ; it [illegible] as low as 3 : 1, while it [illegible] higher than 5 : 1.

[illegible] OF OLIVINE, AND OF PYROXENE, TO SERPENTINE

[illegible] forsterite in [illegible] alternative processes [illegible]. Since in forsterite [illegible] Mg_2SiO_4 [illegible] serpentine 3 : 2, it is clear [illegible] either [illegible] magnesia. If [illegible] some new [illegible] under discussion the possi- [illegible] the formation of carbonate or silicate [illegible] and (2a) [illegible]

(1) $3Mg_2SiO_4 + SiO_2 + 4H_2O = 2H_4Mg_3Si_2O_9$

Increase in volume 10 per cent.

(2) $2Mg_2SiO_4 + CO_2 + 2H_2O = H_4Mg_3Si_2O_9 + MgCO_3$

Increase in volume 33 per cent.

The change of volume is calculated from the usual formula, using the molecular volumes which the minerals and substances have at the ordinary temperature and pressure, and neglecting the volume of the water and gaseous substances which enter into the reaction.[4] In the case of equation (2), if the excess magnesia were removed, either as carbonate or in solution, the expansion would be 24 per cent instead of 33 per cent.

(2a) $5Mg_2SiO_4 + 2SiO_2 + 6H_2O = 3H_4Mg_3Si_2O_9 + MgSiO_3$

In the last equation, the MgO not required for the formation of serpentine is represented as combining with additional SiO$_2$ to form MgSiO$_3$ (enstatite); as stated below however (equation (5)) it is probable that this molecule, if formed at all, would immediately react with one of Mg$_2$SiO$_4$ to produce, on hydration, more serpentine. The reactions (2a) and (5) combined are thus, so far as the end product is concerned, identical with reaction (1); the difference lies in the formation, momentarily perhaps but still continuously, of the molecule MgSiO$_3$. Its continuous formation and destruction during the change from forsterite to serpentine would be a little suggestive of the behavior of certain catalysers.

So far, the olivine has been considered as an iron-free variety. Supposing now that it is iron-bearing, it may chance that it already contains magnesia and silica in the exact proportions requisite for the formation of serpentine, without any addition of SiO$_2$ or removal of MgO. If its iron content separates in part or wholly as magnetite, it is necessary to presuppose the presence of oxygen in some available form, to convert a portion of the iron from the ferrous to the ferric condition. The following equation (3) represents such a reaction.

---

[4] The molecular volumes used are those given by Van Hise ("A Treatise on Metamorphism," U. S. G. S. Monograph, Vol. XLVII).

$$(3)\qquad 3Mg_3FeSi_2O_8 + 6H_2O + O \rightarrow 3H_4Mg_3Si_2O_9 + Fe_3O_4.$$

Increase in volume 30 per cent.

This represents an olivine containing magnesium and iron in the proportion 3 : 1, a ratio which, according to the estimate made above, is not often reached in the olivine of this area; and the resulting mixture of serpentine and magnetite would contain rather more than 12 per cent. of magnetite by volume.

An olivine of this composition might, however, conceivably give rise to serpentine in other ways, such, for instance, as the following:

$$(4)\qquad \begin{aligned} &3Mg_3FeSi_2O_8 + 3CO_2 + 4H_2O + O \rightarrow \\ &\qquad 2H_4Mg_3Si_2O_9 + Fe_3O_4 + 3MgCO_3 + 2SiO_2. \end{aligned}$$

The increase in volume is here 37.13 per cent., while if the $MgCO_3$ and SiO_2 are removed, there is a decrease of a little over 8 per cent.

Equations such as these might be multiplied indefinitely, by imagining olivines of different compositions to react with waters either free from or containing varying amounts of SiO_2 or CO_2, together with some form of available oxygen; and although an increase in volume is common to all such reactions when the total products are taken into account, they quite commonly show a decrease, as in equation (4), when carbonated waters are the reagent and only the serpentine and magnetite formed are considered.

While the reactions which might be postulated are thus innumerable, their final analysis reveals the following:

(1) An olivine which contains Mg and Fe in the ratio 3 : 1 might give rise to an iron-free serpentine by simple hydration (plus oxidation), without any addition or removal of either silica or magnesia; in such a case, the whole of the iron must separate as oxide, a part or the whole of it being oxidized to the ferric state.

(2) Olivines with Mg : Fe = < 3 : 1, *i. e.*, containing more iron than the above, may similarly change to iron-bearing serpentines, by simple hydration plus oxidation, and without any gain or loss of either silica or magnesia, *e. g.*, for Mg : Fe = 1 : 1.

$$3Mg_2Fe_2Si_2O_8 + 6H_2O + O \rightarrow 3H_4Mg_2FeSi_2O_9 + Fe_3O_4.$$

(3) *Olivines with Mg : Fe = > 3 : 1, i. e., in which less than one fourth of the magnesium is replaced by iron, can on no account become altered into serpentine, either iron-free or iron-bearing, except by (a) the addition of* SiO_2 *or (b) the removal of MgO.*

The peridotite of the area is seldom or never made up entirely of olivine: it usually contains some pyroxene, and, with increase in the latter mineral, the rock passes over into pyroxenite, although it is true that in the Black Lake-Thetford area, good asbestos deposits (and consequently, wide serpentine bands) are found only associated with the peridotite. However, some pyroxene is commonly present, and this may be the orthorhombic variety, enstatite, or a monoclinic pyroxene, such as diallage.

Enstatite might react directly with forsterite to produce serpentine, as follows:

$$(5) \qquad MgSiO_3 + Mg_2SiO_4 + 2H_2O \rightarrow H_4Mg_3Si_2O_9.$$

Increase in volume nearly 50 per cent.

The possibility of such a reaction as this taking place is increased by the fact that when serpentine is fused it yields a mixture of enstatite and forsterite,[5] and there can be little doubt that this reaction follows the usual rule, and is reversible under suitable conditions.

Enstatite itself, of course, sometimes alters to serpentine, but being a more acidic mineral than the latter, the change must always be accompanied by the setting free of silica. An iron-bearing enstatite (or hypersthene) might give rise to serpentine, magnetite and silica by a reaction corresponding to (3) above, and, theoretically at least there might be a decrease, instead of an

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[5] A. Daubrée, *Compt. Rend.*, Vol. 62, 1866.

[illegible]

[illegible]

[illegible]

[illegible] more than 50 per cent of all the [illegible] If the p[illegible] with partial oxidation [illegible]

[illegible]

[illegible]

In favor of some such reaction having taken place is the general absence of calcite veins from the rocks of the area, and especially the occurrence of veins of silicates high in lime such as vesuvianite, diopside and grossular garnet; and it is significant that veins of the latter kind are found most frequently, so far as present observations go, not in the vicinity of asbestos deposits, but adjacent to the chromite ore bodies, which are associated with a rock containing considerable amounts of pyroxene. These occurrences are described in more detail below.

In any case, in so far as the Black Lake area is concerned, the further consideration of the monoclinic pyroxenes as an important source of the serpentine may be disregarded, and the same applies, in a lesser degree perhaps, to enstatite also. In the first place, the peridotite here contains in the neighborhood of 90 per cent. olivine, and microscopic examination of thin sections of the serpentine shows that the whole of this olivine has been completely altered; and secondly, of the relatively small amount of pyroxene present in the original rock, some at least has resisted the processes of metamorphism, and may still be seen as occasional crystals within the massive serpentine. The pyroxenes have evidently played a more important rôle in the genesis of the Broughton serpentine, and are doubtless also the source of the talc commonly associated with it.

NATURE OF REAGENTS PRODUCING THE METAMORPHISM.

The change which takes place in olivine is essentially one of hydration: but only in olivines of certain compositions, *i. e.*, those in which one fourth or more of the Mg is replaced by Fe, is hydration (plus oxidation) alone sufficient to bring about the change. The metamorphism of any olivine containing less iron than this requires the presence of some agent or agents in addition to water, and this additional material either enters into the molecule of the resulting serpentine, or is necessary in order to combine with those constituents of the original mineral which are not required for its formation.

In the present case, the evidence points to the olivine as being [illegible] Mg [illegible] Fe [illegible] and its [illegible] as compared [illegible] in SiO_2, or (2) a loss of MgO. Reaction with [illegible] the first result, while in the [illegible] MgO is generally regarded as entering [illegible] under [illegible] of waters [illegible] CO_2.

In [illegible] contained [illegible] as ferrous oxide, [illegible] oxygen in [illegible] the ferrous oxide may be [illegible] to the ferric state. In the present [illegible] the original [illegible] the resulting serpentine, the [illegible]

Assuming [illegible] formula [illegible] and $H_{[illegible]}Mg_{[illegible]}Fe_4Si_{11}O_{[illegible]}$ [illegible] serpentine re[illegible] produced through the agency of [illegible] would proceed somewhat as follows:

$$(8a)\qquad 3Mg[illegible]FeSi[illegible]O_{[illegible]} + SiO_2 + 10H_2O + O \rightarrow 5H_4Mg_3Si_2O_9 + Fe_3O_4$$

The [illegible] here is 37 per cent., and the resulting [illegible] magnetite [illegible] 7 [illegible] per cent. magnetite [illegible]

If [illegible] serpentine of the calculated composition [illegible]

$$(8b)\qquad 13Mg[illegible]FeSi[illegible]O_{[illegible]} + 5SiO_2 + 13H_2O + 2O_2 \rightarrow H_{[illegible]}Mg_{[illegible]}Fe_4Si_{11}O_{[illegible]} + 4Fe_3O_4.$$

The [illegible] 38 per cent.; magnetite [illegible] 7 per cent. of [illegible]

Should [illegible] of the change be brought about by carbonated waters, the equation might be written

$$(9)\qquad 6Mg[illegible]FeSi[illegible]O_{[illegible]} + 3CO_2 + 18H_2O + O \rightarrow 6H_4Mg_3Si_2O_9 + 3MgCO_3 + 2Fe_3O_4$$

Total increase in volume = 34 per cent.; eliminating $MgCO_3$ = 25 per cent.; the serpentine-magnetite mixture contains 8½ per cent. magnetite by volume

$$(9a) \quad 132Mg_5FeSi_3O_{12} + 75CO_2 + 396H_2O + 41O \rightarrow 9H_{88}Mg_{65}Fe_1Si_{44}O_{198} + 75MgCO_3 + 41Fe_3O_4$$

Total increase in volume = 35 per cent.; eliminating $MgCO_3$ = 24 per cent.; the serpentine-magnetite mixture contains 8 per cent. magnetite by volume

The volume relations are approximate, owing to the fact that the molecular volumes of olivine and serpentine of these compositions are not known: for the former, the value given by Van Hise for the compound with Mg : Fe = 3 : 1 is used, and for the latter the volume of the iron-free variety.

In each case the iron liberated is shown as separating in the form of Fe_3O_4; as is well known, magnetite is always present in the serpentine, and it is very possible that some at least of the magnetite which occurs disseminated through this rock, and also especially as a granular film along the centers of the asbestos veins, was derived from iron originally combined in the olivine of the peridotite; on the other hand, much of it may be magnetite which was present as such in the peridotite, and which remained unaffected by the metamorphic changes, except in so far that it may have been segregated and transported (possibly aided by its magnetic character) to the films just referred to, which marked in fact the positions of the fractures from which the alteration proceeded.

According to the above equations, the amount of magnetite produced is about the same in either type of reaction, and it is probably not in excess of that actually met with in the serpentine.

If siliceous waters are presumed to have been responsible for the alteration, magnetite is the only product, in addition to serpentine, which need necessarily be formed; by the action of carbonated waters, however, there must also result a considerable amount of $MgCO_3$, which, if formed, must have been completely removed as there is no evidence of it in the rocks [illegible] it will be found that the $MgCO_3$ [illegible] would occupy [illegible] relatively to the serpentine:

[illegible] serpentine : magnesite = 3 : 1 by volume.
[illegible] 1 by volume.
[illegible], serpentine : magnesite [illegible] to 1 by volume.

If the [illegible] the olivine and serpentine have the composition [illegible] and (c), and the magnesite was [illegible] as great as [illegible] Dresser's estimate that entire serpentine [illegible] massive serpentine asbestos [illegible] if the olivine approaches more nearly to forsterite [illegible] there would be more magnesite than as [illegible]. Actually the relative amount of magnesite would be [illegible] greater than [illegible] the above figures, [illegible] serpentine in the [illegible] whereas the rock beyond these bands has also been [illegible] appreciable degree.

While it may be readily admitted that $MgCO_3$ would be easily soluble under the conditions obtaining (hot solutions of CO_2 under high pressure), it hardly seems possible that, having once been produced in such comparatively large quantities, its removal could have been so complete as the field evidence would show to be necessary.

The difficulty which arises in accounting for the complete disappearance of the $MgCO_3$ is thus a strong argument against the hypothesis that carbonated waters were the agent of the metamorphism, and indirectly it favors siliceous waters as the active reagent, since the sole products in this case, serpentine and magnetite, are those which are actually met with. Moreover, as shown below, direct evidence indicating the presence of siliceous waters is not wanting, while there is nothing to show that waters charged with carbon dioxide were necessarily present at the time the alteration took place.

Summarizing, we find that siliceous waters, which were almost certainly available, are capable of reacting with olivine to give rise to serpentine (with magnetite also if the olivine is iron bearing) and no other product: this is in complete accord with the actual field occurrence.

The presence of carbonated waters, on the other hand, is entirely problematical, and even improbable; further, their reaction with olivine to give serpentine necessarily involves the simultaneous production of $MgCO_3$, and since the latter is not found accompanying the serpentine of this area, there arises the additional difficulty of accounting for its absence.

The conclusion is therefore drawn that the serpentine of the Black Lake-Thetford area has been derived from the alteration of the peridotite through the agency of siliceous waters.

THE EXPANSION ATTENDING THE ALTERATION.

The total expansion is about the same, whether the change is regarded as having been effected by siliceous or carbonated waters, although, obviously, if the carbonate formed in the latter case is removed, there must be a lesser increase in volume, since some magnesia is abstracted from the original olivine and carried away. At first it might seem that the amounts of expansion indicated are excessive, if not impossible, and that, if anything, they are an argument in favor of carbonated waters having produced the alteration; but they cease to be surprising when the volume of the peridotite affected is considered in relation to the whole mass of the rock. In the most extreme case, Dresser[6] refers to the asbestos veins as "occupying in places as much as 10 per cent. of the entire rock." Since he also estimates that the serpentine bands average 6.6 times the width of the asbestos, this would indicate that, in this favorable and exceptional case, the rock as a whole would be composed of 66 per cent. serpentine and 34 per cent. peridotite. In reality there would be considerably less serpentine, owing to the proximity of the asbestos veins to one another and to their many intersections, with consequent lowering of the ratio 6.6 : 1. However, taking the

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[6] *Op. cit.*, p. 65.

[illegible] serpentine [illegible], and assuming the extreme case of complete [illegible] of 40 per cent, this volume of serpentine [illegible] produced from 47 of peridotite, [illegible] relative volume of 34 + 47 or 81, [illegible] to 100, [illegible] of about 23 per cent. [illegible] the water has [illegible] the amount of [illegible] if a [illegible] the [illegible] less than 2 per cent.

[illegible] had in [illegible] and the [illegible] That [illegible] more than 90 per cent of [illegible] specimens of [illegible] asbestos absent, which can only mean that [illegible] apparently unaltered rock has been changed in a very [illegible] degree to serpentine, whereas Dresser's estimate of the relative volumes of massive serpentine and asbestos refers to [illegible] which the metamorphism has been practically complete. [illegible] however, it is probable that the expansion [illegible] the whole mass of the peridotite, as a result of [illegible] alteration to serpentine, has not amounted to [illegible] per cent.

[illegible] PRODUCING THE METAMORPHISM.

[illegible] waters have been responsible for the [illegible] peridotite, the question arises as to whether they were of meteoric or magmatic origin.

[illegible] the serpentine [illegible] at a [illegible] the earth's surface [illegible] the case. The [illegible] and [illegible] of serpentine and asbestos with depth, although on the latter point little is definitely known, as our knowledge extends only for a few hundred feet below the present surface. The peridotite itself has all the characters of a deep seated plutonic rock, and always lies below the other igneous rocks with which it is associated, *i. e.*, if the igneous complex takes the form of a batholith or stock, peridotite forms its central part, if a sill, the base. These features however provide no unanswerable argument in favor of the origin of the serpentine at depth, since the serpentinization might still be a comparatively recent phenomenon, which commenced after the erosion of the area, or progressed continuously with it.

If however it is admitted that the metamorphism is intimately connected with the intrusion of the granite dykes, then it follows that the conditions necessary for the alteration were brought about at a time long previous to the truncation of the overlying rocks, and at a depth far below the then existing surface. This would follow since the granite was intruded not much later, geologically, than the consolidation of the peridotite itself; and once the conditions favorable to the formation of serpentine arose, there is no reason to suppose its production was delayed. The field evidence undoubtedly points to the granite as having favorably influenced the formation of serpentine, since the number and width of the bands of this mineral may frequently be seen to increase in the vicinity of the dykes; and this circumstance affords the best confirmation of the hypothesis that the serpentine was formed at depth. It is of course evident that the rocks were not below the zone of fracture, for it is impossible to conceive of alterations of this type accompanied by an expansion of the rock masses, as taking place within the zone of flowage.

Incidentally, the hypothesis that the serpentine has originated at such depths is distinctly unfavorable to the possibility of carbonated waters having played any part in its formation; not because such waters could not have descended to the scene, but owing to the improbability of the magnesium carbonate formed during the reaction being able to leave it.

The mere fact of depth does not preclude the possibility of the metamorphism having been brought about by descending meteoric siliceous waters. Since however the decision lies between a problematical supply of such waters, and an almost certainly established source of available magmatic waters which fully explain all the relations, both on theoretical grounds and as seen in the field, it seems more logical to regard the latter as the agent which has affected the alteration of the peridotite.

EVIDENCE THAT MAGMATIC SILICEOUS WATERS WERE AVAILABLE.

Direct evidence that the granitic injections were accompanied by hydrothermal waters, capable of producing somewhat intense pneumatolytic action, is supplied by certain dykes of vesuvianite, grossularite garnet and diopside which are found cutting the serpentine in many of the asbestos and chromite pits, particularly the latter. These dykes are, as a rule, white or light colored (some of those composed of vesuvianite are deep lilac) and fine grained, although occasionally they are very coarsely crystallized, as is the case with some diopside dykes at the Montreal chrome pit. Except on close examination, therefore, they might easily be mistaken for ordinary aplite or pegmatite dykes, and it is no doubt largely owing to this that their true character has been generally overlooked in the past and that they have not been distinguished from the granitic dykes. So far as can be found, there has hitherto been no mention of the occurrence of such dykes in the published descriptions of the geology of the asbestos pits, while the lilac vesuvianite dykes at the Montreal chrome pit are specifically referred to by Cirkel[1] as "granite." The first record that the latter are not granite appears in Dresser's report, and the specimens which he collected proved, on examination by the writer, to be composed entirely of the mineral vesuvianite. Dresser[2] describes the mineral as occurring in "sheets, veins and irregular vugs" at several of the chromite pits, and he states that

"The occurrence of vesuvianite in two of the chromite deposits indicates that there has been pneumatolytic action. But granite intrusions which are found near each of these deposits were formed somewhat later than the rock which contains the chromite. It is, therefore, certainly possible, and seems more probable, that the vesuvianite was formed by pneumatolitic action due to the intrusion of the granite, rather than to the intrusion of the basic rocks."

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[1] Report on the Chrome Iron Ore Deposits in the Eastern Townships of the Province of Quebec. By Fritz Cirkel, Mines Branch, Dept. of Mines, Ottawa, Canada, 1909, page 27.

[2] Op. cit., pp. 89 and 90.

Examination has shown that these lime-silicate dykes are by no means limited to the vicinity of the chromite deposits, but that they occur also, though perhaps not so commonly, cutting the chrysotile-rich serpentine. Further, there seems to be definite confirmation of Dresser's view that they are intimately related to the granite dykes, and that they have resulted from pneumatolitic action accompanying the injection of the latter.

The field evidence on this point is as follows: Aplitic dykes of normal character, containing little or no garnet are frequent, but occasionally they are found to be highly garnetiferous, while in other cases the aplite is traversed by narrow veinlets of fine granular garnet. It is difficult to avoid the impression that all gradations exist between the normal aplite and the dyke composed entirely of garnet, and that an aplite might be found to gradually change into a garnet (or vesuvianite or diopside) dyke in one and the same continuous fissure, although such an ideal case has hitherto not been observed.

The mode of origin of these dykes has been discussed by E. Poitevin and the writer in a monograph[9] dealing with the mineralogy of the Black Lake area, and may be briefly summarized as follows: In the first place it is very evident that these lime-alumina silicates have not been produced through the contact metamorphism of impure limestones, since the sedimentary series into which the peridotite and related rocks have intruded does not include any limestone beds, and further the occurrences have the attitude of ordinary dykes, enclosed on each side by serpentine. The only possible source of the lime, and also of the alumina, which these minerals contain, is apparently to be found in the pyroxene of the peridotite and pyroxenite bodies. It is believed, therefore, that the granitic magma, as it made its way along fissures in the peridotite and associated rocks, was able to exert a

[9] Museum Bulletin, Geol. Survey Branch, Dept. of Mines, Ottawa (in press)

[illegible] that [illegible] the [illegible] has [illegible] encountered, owing [illegible] to [illegible] in extent and composition and loss of content of aqueous and other volatile constituents; and as a result the [illegible] of these [illegible] have been removed in solution. The magma, after assuming [illegible], according to [illegible], aplite, [illegible] aplite or compact garnet dykes, [illegible] diopside [illegible] has been found [illegible] garnet.

Whether the process [illegible] applying all the isolated injections of granite [illegible] cannot be determined, but it is possible [illegible] most or all of the granite dykes [illegible] upward [illegible] gradual transition [illegible] dykes of [illegible], and that the present comparative rarity of the latter is due to their having been removed by erosion, which in most cases has left only the normal granite roots of the dykes.

The composition of the invaded rocks would also be an important factor in determining their formation, and might explain the fact that such dykes seem to be relatively more abundant near the [illegible] deposits than with the chrysotile; the former are all associated with a rock approaching a pyroxenite, while the chrysotile occurs in a rock which was originally a peridotite extremely poor in pyroxene.

If this hypothesis correctly explains the genesis of these lime-[illegible] dykes, it affords proof that the granitic magma, at least under certain suitable conditions, was capable of exerting a profound solvent action on the walls of the fissures it traversed. The material which has given rise to dykes of such acid composition as aplite is now generally regarded as having been, not so much in a molten state, as in the condition of a solution, or aqueo-igneous fusion. If it is admitted that such a solution was capable of dissolving and secreting material from the walls of the fissures [illegible], the writer would draw the conclusion that the [illegible] mother liquors not required for the formation of the garnet and lime silicate dykes were also capable of finding their way along many of the more or less closed joints and other cracks in the neighbouring rock, insinuating themselves into the narrowest crevices and bringing about the alteration of the rock on either side to serpentine.

This hypothesis is quite irrespective of the actual age of the granite dykes, to which reference has already been made.

It may be objected that the number and size of the exposed granite dykes and masses are totally inadequate to have been responsible for serpentinization on the scale which has actually occurred, and that, even if the alteration has been effected by siliceous magmatic waters, these could not possibly have been derived entirely from the granitic magma. This question resolves itself largely into a matter of opinion as to the relative amount of such waters which might accompany a granitic magma, and that this amount has been variable at any given horizon in the Black Lake area is probable from the fact that the granite dykes do not always seem to have had an equal influence on the degree of serpentinization of the adjoining rock. There is also the possibility that the exposed dykes are merely the offshoots of larger bodies of granite which have not yet been uncovered; this might even be regarded as a probability should it ever be proved that the dykes belong to a later period of igneous activity than do the basic rocks of the serpentine belt, a view which is not held by those who have examined the area carefully. On the other hand, hydrothermal siliceous waters capable of producing serpentinization may have escaped from the peridotite magma as it crystallized, either before it had reached the extreme composition of a granite, or, in other cases, where the differentiation never proceeded so far. If such was the case, serpentinization would have commenced prior to the injection of the granite dykes; but the mode of occurrence of the serpentine in "bands" indicates that, at least in the main, the alteration of the rock originated along joint planes, and if, as believed by the writer, these were injected by the granite soon after their formation, the hypothesis here outlined for the origin of the serpentine is not materially affected.

The peridotite, then, within the zone of fracture, may be supposed to have been still at a fairly high temperature, but cooling. The stresses set up under these conditions within the contracting mass were relieved by a general shattering along well defined systems of joint planes, and also by subsidiary fractures. Any open fissures so produced, or rather, perhaps, the more pronounced and continuous fissures, were injected by granitic magma, which represented the last and most acid differentiate of the original magma from which the peridotite itself was the first portion to separate. In this way there originated the granite dykes which are so prevalent cutting the peridotite in the vicinity of the serpentine bands. The acidic, *i. e.*, highly siliceous, magmatic "extract" not required in the formation of the granite, and which contained all the water and other volatile constituents of the original magma, may well be supposed to have found its way along the joints and crevices in the surrounding peridotite, and to have exerted a very intense action on the rock, from which it differed so widely in chemical composition.

The writer would draw a strict analogy between these siliceous solutions and the quartz veins and stringers which are so commonly met with traversing bodies of granite, at least in so far as their source is concerned.

In the case of large granite masses, it is common to find that the last phases of intrusion have taken the form of aplitic or pegmatitic dykes, which are more acid in composition than the main body of granite; they are, in other words, acid differentiates of the same magma which supplied the granite, and consequently are quite comparable with the granite (and aplite) dykes cutting the peridotite in this area, except that the differentiation in the former case has not given rise to rocks of such extreme compositions as in the latter. The granite, further, is usually traversed by still more acid veinlets, which in many cases are pure quartz; these represent the last remaining fraction of the magma which has been left over after supplying the material of the dykes. Such highly siliceous magmatic solutions have traversed the fissures and cracks in the surrounding granite, but the latter rock being itself composed largely of quartz, with other fairly acid minerals, there was no tendency for any reaction to take place, and the solutions depositing their silica have given rise to stringers or irregular veinlets of quartz.

Many instances might also be cited of quartz veins, often of considerable size, traversing granite, or even basic rocks, and which are clearly of pegmatitic character. Where such quartz veins traverse basic rocks and have not appreciably altered them, it is no doubt mainly because the rock and the quartz vein are not genetically related in any way, *i. e.*, the temperature of the siliceous solutions was low, and the invaded rocks had themselves long reached a temperature in equilibrium with their surroundings.

In the present case, however, the peridotite, granite and siliceous solutions were all originally present together in the same magma, and there was no great time interval between the consolidation of the first and the rendering available of the last. Such solutions, then, instead of meeting with acid minerals as they traversed the fractures in the surrounding rock (as in the case of the granite considered above), came in contact with olivine, the most basic of all the (igneous) rock-forming minerals, and also one of the most easily solube; and instead of merely depositing their silica along the fissures in the form of quartz veins, they reacted with the olivine to produce the less basic and more insoluble mineral, serpentine.

The alteration of the peridotite would thus go on progressively outward in both directions from the joints or crevices which served as channels for the supply of the necessary reagent. The width of the resulting band of serpentine would depend on several conditions, but mainly no doubt on the composition and texture of the original rock, the prominence of the fissure, its proximity to the main sources of supply of reagent, and on the continuance of the latter. This would explain why the widest and most persistent bands follow the rectilinear major joint system of the peridotite, those having other directions or more irregular courses being in general narrow. Further, given a fairly constant composition and texture for the peridotite, the rate of reaction should be approximately the same on each side of the fissure throughout its course, yielding bands with roughly parallel boundaries about equi-distant from the central crevice. It would be expected that these boundaries against the unaltered peridotite would be somewhat transitionary, and not sharply defined like the walls of a dyke, and such is borne out by the field evidence.

It is true Dresser[1] states that [illegible] "[illegible] not quite so sharply defined [illegible] as that between the peridotite and serpentine," but the [illegible] portions of peridotite [illegible] beyond the serpentine band proper there is a zone of rock which has been serpentinized to a very considerable degree.

As a result of his observations in the field, Dresser has concluded that the serpentine [illegible] to occur along planes [illegible] strain fractures [illegible] found along fractures [illegible] the peridotite, and which he assigns to [illegible] about the formation of the [illegible] in fractures, he is [illegible] that such waters [illegible] had access to the [illegible] peridotite, and that the serpentine now found along [illegible] waters.

These "exfoliation" fractures are in general smaller than those of the other two classes, and are of minor importance. Dresser[2] defines them as "fractures caused by exfoliation, or the casting off of concentric shells from irregular blocks which have been previously separated from one another by fractures of the two preceding classes (i.e., joints and strain fractures). The increase in the volume of the rock when it is altered from peridotite to serpentine probably aids in forming fractures of this class."

The writer's view is that while the major bands of serpentine do undoubtedly appear to be along the master joints due to shrinkage of the peridotite while cooling, and others may follow strain fractures formed by regional compression, the minor bands are so irregularly situated that it is impossible, with any degree of certainty, to assign any particular origin to the cracks they border. Many examples may be seen, especially on the vertical walls in the asbestos quarries, where the rock is intersected in a truly amazing manner by [illegible] enclosed with serpentine bands [illegible] crossing one another at every angle, some fairly straight and others curved or quite irregular in their course. [illegible]

[1] Loc. cit., p. [illegible]

[2] Loc. cit., p. [illegible]

[illegible] rectilinear joints. Even if it could be demonstrated that some of these fractures are the result of exfoliation, the writer agrees with Dresser that their formation would have been aided by the expansion of the rock during its conversion to serpentine. While this would presuppose that some serpentinization had already taken place before the cracks of this type came into being, it does not thereby follow that the alteration of the rock bordering them began at a much later period than that along the main fractures. Expansion must have started and continued *pari passu* with serpentinization; and there seems no valid reason for supposing that the same siliceous waters which affected the one set of fissures did not also have access to the other. The fact that these "exfoliation" bands are in general narrow would indeed lend support to the view that serpentinization along the cracks they follow commenced somewhat later than in the wider ones.

Finally, the serpentine bordering such minor cracks is quite indistinguishable from that in the main bands, and where the two sets meet or intersect there is a continuity of the massive serpentine, and no break or other irregularity which might indicate that the mineral was formed, in the two cases, at widely different times or by different processes.

Since the evidence lends a fair degree of probability to the hypothesis that the whole of the serpentine was formed essentially at one time, or at least that its production, once begun, was continuous, and in the absence of any facts proving the contrary, it is here concluded that all the serpentine in the area has originated in one and the same way, through the agency of siliceous waters of magmatic origin.

An additional point which should be considered is that the serpentine is cut by granite dykes. In this connection Cirkel says:[12]

> "The serpentine is often cut by intrusive dykes of granite, which, as they fill fissures in the formation, appear to be of younger origin than the surrounding ground. . . . Sometimes these dykes cut off good asbestos entirely; but, as a general rule, good ground is found on the other side of the dyke mass."

[12] "Chrysotile-Asbestos," *op. cit.*, p. 75.

At first sight such a feature appears to completely invalidate the whole hypothesis of the origin of the serpentine as outlined above, since, if the granite dykes are really later than the serpentine, it would seem impossible that the siliceous waters associated with their intrusion could have had any bearing on the production of the mineral. It is probable, however, that the conclusion drawn by Cirkel as to their relative ages is erroneous, and the phenomenon certainly admits of a simple explanation which is in complete accord with the theory that the dykes were intruded prior to the formation of serpentine.

The hypothesis practically demands a shattering of the peridotite, probably due to contraction of the cooling mass, before the intrusion of the dykes; in fact, without fracturing there could be no dykes. But it is not supposed that the intrusive magma welled up through all the fissures of the joint system, or even through an appreciable percentage of them; it made its way along the paths of least resistance, wherever it could force apart the walls of the fissures. The large majority of the joints doubtless remained closed, and so it is not surprising to find instances in the field where dykes cut across such fractures. At the time the dykes were intruded, however, the rock was peridotite, and it was only subsequently that serpentine began to be formed through the agency of the siliceous solutions expelled from the granite magma, and containing all the water and other volatile constituents of the parent magma. These solutions, aided no doubt by the low viscosity they possessed in virtue of their composition, may be imagined as percolating through all the more or less closed joints and other fissures in the vicinity of the dykes, and by a process of soaking into the peridotite to have brought about the gradual replacement of its olivine (and pyroxene) by serpentine.

Where a dyke intersected one of these joints, serpentinization may have proceeded along the latter on each side of the dyke, and it would even be remarkable if such did not happen, under the favorable circumstance of close proximity to the dyke. The result would be that, when laid bare by erosion, such an occurrence would present the apparent paradox of a dyke cutting the serpentine band.

THE ORIGIN OF CHRYSOTILE ASBESTOS.

Views as to the manner in which the chrysotile has originated are somewhat at variance, but it is probable [illegible] that the weight of modern opinion is in favour of the hypothesis that it has been formed *in situ* by [illegible] of the serpentine [illegible].

Reference to the literature on this question will be found in the reports of Cirkel and Dresser, and it is not necessary here to refer further to the [illegible] views which have been [illegible]. Dresser [illegible] summarizes the evidence, and his conclusions, relating to the origin of the chrysotile, as follows:[13]

"The position, size and number of asbestos veins in rich ground make it practically certain that the spaces they now occupy were never open fissures, and especially that many of them were open at the same time. Open fissures up to 2 inches in width, running in all directions from vertical to horizontal, extending 10 feet or more in length and occupying in places as much as 10 per cent. of the entire rock, would be a mechanical impossibility. The possibility remains of crevices having been enlarged and filled by replacement.

"But the asbestos of the veins is practically identical in chemical composition with the serpentine of the walls, which is strong evidence against the material composing the veins having been brought in either from above or below. Segregation from the walls also would imply a difference in chemical composition, which does not exist. In other words, the material removed would have been replaced by material of exactly the same chemical composition, which is altogether improbable if not impossible.

"It is therefore concluded that the veins are crystallized portions of the serpentine walls, and that the crystals (fibres) have grown outwards from the original crevices which are now represented by partings of iron ore found near the center of the veins. In cases where there is no such parting the growth of the crystals has taken place on one side of the fracture only. In most cases, however, there has been crystallization on both sides of the fracture, thus leaving a parting in the vein."

The writer's views coincide with the above. In addition, as first pointed out by Dresser, there appears to be a constant ratio between the width of any asbestos vein and that of the serpentine

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[13] *Op. cit.*, pp. 65-66.

[illegible]

[illegible] However, the [illegible] feature is re- [illegible] specimens. The [illegible] necessarily [illegible] the chrysotile [illegible] the massive serpentine; but [illegible] parlance, [illegible] hand specimens. The [illegible] large measure, [illegible] the two materials possessing such totally different structures, and also to [illegible] difference [illegible] and lustre. In the case of the [illegible] between [illegible] massive serpentine, which is [illegible] defined as that between the latter and the chrysotile [illegible] is not so pronounced, because both materials [illegible] similar in color that on freshly broken surfaces it is often a matter of difficulty to distinguish [illegible]

[illegible] degree of probability to the [illegible] replaced massive serpentine, [illegible] of the causes which have been responsible for the change, nor offers any suggestion as to the [illegible]. In order to obtain possible evidence on this point, the relation between massive serpentine and chrysotile may first be considered.

[illegible]

[illegible]

[illegible] weight should be attached [illegible] whether they are to be considered as exact analyses. [illegible] of all the analyses indicates that there is [illegible] difference in the chemical composition of [illegible]

[illegible] ore, which is always present [illegible] concentrated along the central parting plane [illegible] whereas in the massive serpentine it is irregularly disseminated [illegible] unless very special precautions are taken [illegible] for analysis, there is much greater danger of an admixture of magnetite in the latter case than in the former. Practically all the analyses show some Al_2O_3 in both varieties, and Connor's results suggest that this constituent is present in greater amount in the massive serpentine. The figures given by Cirkel are not so conclusive, and, especially in the chrysotile analyses, they are rather widely divergent, ranging from *nil* to 3.67 per cent. It is significant, however, that in each of the four analyses given, there is a corresponding fluctuation in the MgO content, and further that a high percentage of Al_2O_3 is accompanied by a low percentage of MgO, and vice versa, which might possibly mean that some MgO was precipitated along with the Al_2O_3, as commonly happens in the analysis of substances containing large amounts of magnesia unless the precipitate with ammonium hydrate is dissolved and re-precipitated several times. Also owing to the fact that the Al_2O_3 is precipitated in the course of the analysis together with the iron, and estimated by difference after the reduction of the latter, any incompleteness in the reduction process throws an [illegible] Al_2O_3 [illegible] of Al_2O_3 [illegible] in the [illegible] Lastly, [illegible] massive [illegible]

[illegible] similar, [illegible] massive [illegible] such as magnetite and unaltered [illegible] massive [illegible] from [illegible]

[illegible]

[illegible] fairly [illegible] between 2.50 and 2.65. These extremes [illegible] of well-crystal[illegible] varying [illegible]

In [illegible], however, [illegible] seen that there is a very wide [illegible] determinations which have been published. Dana,[1] for instance, reproduces some analyses [illegible] gravity [illegible] from 2.44 to 2.7[illegible] The same author, [illegible] as 2.60, and [illegible] 2.8, has been reproduced [illegible] descriptions [illegible] In this way [illegible] that the [illegible] at the latter locality is less dense than the massive [illegible] with which it is associated, although apparently [illegible] statement has in no case been based on an actual determination [illegible] the specific gravity.

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[1] System of Mineralogy, [illegible] p. 673

Relying on this as the correct figure, the writer was at first inclined to believe that the lower specific gravity of the chrysotile, as compared with massive serpentine, had been the determining factor, or at least a very important one, in causing the replacement of the latter by the former. Such a replacement would have involved an expansion in volume of more than 12 per cent., or, in other words, an asbestos vein 4½ inches wide would represent what had once been a 4-inch band of massive serpentine. Since the alteration of peridotite to serpentine is itself attended by an increase in volume, it was reasoned that there would be every tendency for any further change, and hence an additional expansion, to take place.

A little consideration showed the improbability of there being such a wide difference in the specific gravity of massive serpentine and chrysotile. In the first place a fibrous structure is not accompanied by a change in density in other substances or minerals (amphiboles, gypsum, etc.), and secondly, if chrysotile represents serpentine in the crystalline condition, as is sometimes thought, it would rather be expected to have a higher density, if anything, than the massive and practically amorphous substance. In order to clear up this point, several determinations of the specific gravity of each variety have been made. In the case of chrysotile, accurate determinations were made on fine threads, freed from all visible magnetite, using the pycnometer, while in other cases whole veins were taken, with as little of the massive serpentine attached as possible, and their specific gravity found by the hydrostatic weighing method. For the massive serpentine, the large pieces were used throughout. The values found are given in the following table.

Except in the case of the larger specimens, the specific gravity was taken after boiling as well as in the ordinary way, and in every such case an appreciably higher value was obtained; in fact, it was found impossible to weigh accurately a piece of massive serpentine immersed in water unless it had been previously boiled, since its apparent weight continually and rather rapidly increases as the water soaks through its pores. The boiling was continued for not less than 2 hours, and the specimen then allowed

bundles of fibers separated by air films, it displaced more water than it would have done had it been in an undamaged and compact condition.

That the massive serpentine is certainly not denser than the chrysotile is shown by determinations [illegible] 8 [illegible] 11), which range from 2.55 to 2.58. The fact that [illegible] these determinations contain very large pores [illegible] the foreign minerals likely to be present (magnetite and pyroxene) are denser than the serpentine itself, might [illegible] be taken as indicating that, if anything, chrysotile is the denser of the two. The lower value [illegible] 12 was obtained on a very dark green serpentine and is [illegible] to be referred to a greater replacement of Mg [illegible] here than in the average serpentine. Numbers 13 and 14 are of interest as showing the effect of distance from the chrysotile vein, the higher values being due to the fact that the serpentine contains a considerable amount of incompletely altered pyroxene.

It would appear, then, that massive serpentine and chrysotile not only have the same composition, but [illegible] the same density, and [illegible] dealing here with a case of [illegible].

No appreciable difference in the hardness of the two are recognizable.

Optical and Microscopic Characters.

In none of its varieties does serpentine exhibit well-defined crystal characters. The [illegible] under the microscope, [illegible] crystalline character. It is biaxial, with rather [illegible] birefringence rather higher than [illegible] quartz. The fibers are optically positive, but certain platy varieties appear to be negative.

In the area under discussion, almost the whole of the serpentine has been derived from the alteration of peridotite, and sections can be obtained showing all stages of this alteration, from the fresh peridotite to the massive serpentine rock. The serpentinization follows the course which is usual under these conditions, commencing around the margins of, and along cracks in, the olivine crystals, and proceeding inwards toward the center of the [illegible] ser- [illegible] crystal [illegible] frequently the serpentine [illegible] the form of parallel fibers, [illegible] arranged. [illegible] further, the [illegible] of the [illegible] most usually [illegible] an irregular [illegible]

[illegible] it is desired to emphasize is that the [illegible] large measure [illegible] in [illegible] parallel to one another. [illegible] specimens of [illegible] readily [illegible]

[illegible] and massive [illegible] The former [illegible] the fibers are [illegible] may be parallel to one [illegible] Where [illegible] are microscopic, with no regular [illegible] up the [illegible] "mas- [illegible]

[illegible] of massive serpentine [illegible] with the [illegible] that [illegible] between them is no doubt realized [illegible] the dif- [illegible] it is probably safe to say [illegible] asbestos and massive serpentine [illegible] to one another in exactly the same way as [illegible]

THE CHANGE FROM MASSIVE SERPENTINE TO CHRYSOTILE.

Granting, then, that massive serpentine and chrysotile are in every way one and the same substance, the question as to the reason for the occurrence of veins of the latter resolves itself entirely into one concerning the conditions favorable to the formation of this more perfectly crystalline form of the mineral.

Although the serpentine they contain is identical in every way, there yet remains a great difference between the constitution of the chrysotile veins and the massive serpentine bands; this difference consists wholly in the absence or presence of admixed material, and depends also upon the nature of the latter. In the veins, the serpentine is absolutely free from any foreign substance other than iron ore, and even this is for the most part segregated along a single plane near the center of the vein. The massive serpentine of the bands, on the other hand, always has associated with it, in addition to magnetite, a certain amount of unaltered, or incompletely altered, pyroxene, and this is true even in the zone immediately adjacent to the chrysotile; the magnetite, moreover, is here widely scattered in grains throughout the bands. It seems reasonable to conclude, therefore, that the first condition necessary in order that veins of chrysotile may form is the complete serpentinization of all the ferro-magnesian minerals of the original rock, together with the complete removal of all other constituents, such as lime and alumina, which may be present, with the exception perhaps of iron ore.

The factors favoring such a complete alteration might not everywhere be the same; but it should be possible, in any particular case, to obtain some indication of their nature from a consideration of the course which the metamorphism has taken.

In the present area, a cross-section from the peridotite to the chrysotile may be divided roughly into four zones, as follows: (1) unaltered peridotite; (2) partial serpentinization of the olivine, with pyroxene more or less unaffected; (3) olivine completely, and pyroxene partially, serpentinized—this zone constitutes the massive serpentine "bands"; (4) complete serpentinization of both olivine and pyroxene—this zone forms the chrysotile "veins."

[illegible] along a portion of the material [illegible] serpentine [illegible] the per- [illegible] has proceeded outwards from the joint planes and other fissures [illegible] and [illegible] have [illegible] the rocks [illegible] appears [illegible] serpentine [illegible] form of [illegible] rendering it [illegible] zones [illegible] from the original fissures [illegible] passage [illegible] partially [illegible] during the [illegible] serpentinization [illegible] reached.

The [illegible] a similar [illegible] increasing with the degree of serpentinization. Thus, the [illegible] of the original [illegible] serpentine [illegible] still [illegible] traced, and [illegible] altered portion [illegible] yet [illegible] in the serpentine. [illegible] the orig- inal structure [illegible] of the [illegible] definite zones.

From [illegible] it would seem to follow that in the early stages of the process, the structure of the peridotite was hardly at all affected, and that until serpentinization was fairly complete, the rock remained essentially a solid mass, although sufficiently porous, partly as a result of its expansion, to admit of the free passage of [illegible] solutions. But the serpentinization [illegible] does ex- [illegible] also a loosening up of the rock and an increase in its porosity, and the latter favors in turn [illegible] the serpentinization. Thus, in the final stages, where the rock has been completely serpentinized, its porosity must be at a maximum, or, in other words, it must be completely saturated with the solutions which effect the serpentinization, and its original structure is lost.

This result is naturally first attained in the zone immediately bordering the fissure, which is then composed entirely of fibers, possibly [illegible] microscopic in length, of serpentine. The [illegible] of the veins is believed to be the result of the parallel position and [illegible] attitude assumed, at the very outset, by these very minute fibers, and of their subsequent growth in one direction only, *i. e.*, outward from the fissure, as successive new zones of rock became completely serpentinized; and the ultimate length of the fibers was limited only by the width attained by this completely serpentinized zone.

In the present state of our knowledge concerning the causes which determine or influence the habit of crystals, it may, perhaps, seem idle to discuss possible reasons for the extremely acicular character of the crystals or fibers. It might be said that this is the common habit of "crystals" of serpentine, just as, for instance, it is the common habit of crystals of mesolite; and it is certain that such a habit may be determined by one or more of several factors, such as the temperature and concentration of the crystallizing liquid or solution, and also by pressure. A crystal growing under ideal conditions, *i. e.*, surrounded on all sides by solution of equal concentration and under the same pressure from all directions, may (except in the case of cubic substances) develop a prismatic habit, more or less pronounced, which is entirely the result of the intermolecular forces set up during crystallization; on the other hand, a growing crystal which is not so surrounded, will have its habit controlled in very large measure by external causes. Generally speaking, it may be said that the crystal will grow only in those directions in which it is in contact with a supply of supersaturated solution, and if only the extremity, or both extremities, of the crystal, are so supplied, there will result an acicular or asbestiform habit.

[illegible] be [illegible]

[illegible] be [illegible] applied or [illegible] in [illegible] solu- [illegible] which would [illegible] the [illegible] from [illegible]

[illegible] while the liquid [illegible] corre- [illegible] When [illegible] it is usually seen that the needles radiate in [illegible] each center or point of crystallization, and it [illegible]

3. [illegible] If a sub- [illegible] with increase in volume, any increase in the [illegible] further growth [illegible] Assum- [illegible] the liquid state or in concentrated [illegible] pre- [illegible] direction [illegible] The crys- [illegible] with [illegible] pressure, [illegible]; moreover in this case the fibers will be [illegible] parallel to one another.

While, then, there may be many alternative ways in which a fibrous habit might originate, the possibilities should be some-

[illegible] the case [illegible] parallelism of the fibers; and [illegible] should be [illegible] found that the attitude of these fibers is always transverse to their bounding walls. Both the parallelism of the fibers and their transverse attitude are structural features which are indicative of an expansive rather than a compressive strain. At first sight it might seem that [illegible] would be impossible or unlikely. However [illegible] serpentinization is attended by an increase [illegible] altered, which might be expected to [illegible]. According to the views advanced here, however, the [illegible] was [illegible] at the time [illegible] undergoing alteration to serpentine, and it seems not impossible that the [illegible] of contraction due to cooling may have been so great, or perhaps its rate may have been so rapid, that in spite of the expansion involved in the [illegible] serpentinization, there was a tendency for the joint planes and other fissures to open, and as a consequence the material adjacent to them was subjected to an expansive strain, normal to the walls.

The full force of such a strain would necessarily be exerted at the fractures, because they were planes of weakness; and it would affect only the completely serpentinized film, or layer, of rock parallel to these fractures, since, as indicated by its structure, the rock beyond remained essentially a solid mass until its [illegible] metamorphism was effected.

Stated briefly, the writer's conclusions regarding the mode of origin of the chrysotile veins are as follows:

Siliceous magmatic waters, rising along fissures in the cooling and contracting peridotite, have soaked into the rock on either side and brought about its serpentinization. Complete alteration under these conditions was first reached in the layer of rock immediately bordering the fissure, while beyond this the degree of serpentinization decreased more or less gradually outward to the unaffected peridotite. Owing to the tendency for the fissures to open, this bordering layer of serpentine was not subjected to a uniform pressure from all directions, and the growing crystals were able to develop only in the direction of least pressure, nor-

[illegible] may been continually [illegible]

[illegible] to counterbalance the expansion attending [illegible]. In this case the formation of serpentine [illegible] proceed, but the rock altered, being [illegible] under a [illegible] pressure, the fibers would not be forced [illegible] relative to the [illegible], and [illegible] would result. The fact that Dresser found [illegible] between the width of the chrysotile veins and the serpentine [illegible] which enclose them, suggests, however, [illegible] proceeded side by side and ceased [illegible] consequently it may be concluded that it was lack of [illegible] reagents which finally determined the width of any chrysotile vein.

[illegible] might be raised that, since the serpentinizing waters, in the course of their passage from the fissure to the unaltered or incompletely altered rock beyond, must have been continually passing across the whole width of the chrysotile vein in process of formation, the delicate fibers would have been redissolved.

[illegible], it does not necessarily follow that a reagent [illegible] of dissolving olivine, and even pyroxene, was an equally potent solvent for chrysotile, and in fact it may have had little action on the latter. The writer is inclined to the view that solution of the fibers did perhaps take place to some extent, [illegible] extremities adjacent to the fissures [illegible] opening of the latter), the material being redeposited further along in the vein. A repeated recrystallization [illegible] go far to explain the extreme delicacy [illegible] uniform character of the chrysotile fibers, and also the absence of admixed foreign material from the veins, since all the iron ore, being insoluble, would be left behind and accumulate at the fissure. It might also throw some light on the frequent wavy or uneven nature of this central parting of iron ore (generally regarded as marking the plane of the original fissure), which is rather difficult to account for, since, on the above view, a partial, but not uniform, solution of the fiber tips might lead to a shifting or wandering to one side or the other of the original place of the fissure.

According to the above hypothesis, two conditions must be fulfilled before veins of chrysotile can form. These are:

1. The production of pure serpentine, *i. e.*, the complete serpentinization of all the silicate minerals of the peridotite, or other parent rock, together with the complete removal of all those constituents which are not required for the formation of the serpentine molecule (except perhaps iron ore).

2. The pure serpentine, as it crystallizes, must be under a differential pressure, *i. e.*, subjected to an expansive strain in one direction, which will determine the direction of elongation of the fibers.

The necessity for the first condition will be generally admitted; and yet there must be some other requisite, or chrysotile would be a very much more widespread and common substance than it actually is. The writer believes this is supplied by the second condition above. The expansive strain may perhaps not everywhere result from the same causes; in the present instance it is

[illegible]

[illegible]

[illegible]

[illegible] these experiments [illegible] of magmatic water [illegible] that these waters were not [illegible] with the parent rock of the serpentine mass [illegible] reacted upon it long after it had reached the [illegible] temperature and ceased contracting; and in many cases, also, it may be that the metamorphism did not progress so far as to realize the [illegible] condition of complete serpentinization.

[illegible] where there are, [illegible] intermediate fissures having [illegible] relations to these and to one another, [illegible] Each fissure, while tending to open [illegible] will be influenced by every other fissure, to an extent depending upon its prominence and nearness, and the direction of the expansive strain at any point will be the resultant of all these combined, and might vary from time to time. As a consequence, the fiber in any particular vein, instead of stretching across normally from one wall to the other, may be disturbed, curved or bent, although at the same time its general direction will be dominated by the attitude of the fissure it follows.

SLIP-FIBER.

This term is used to define those occurrences in which the chrysotile fibers, instead of lying transversely, have their length parallel to the fissure walls. Owing to the manner of occurrence, such fiber may appear to have a very considerable length, but this is due to the overlapping of short fibers which are all matted together in more or less parallel position, and examination shows that the slip-fiber is in reality usually shorter than the average transverse vein-fiber. As the name suggests, the field indications are that this variety of fiber always follows planes of slipping or shearing; there is apparently no evidence to show whether it was formed prior to the cross-fiber veins, or at some subsequent time. This type of occurrence is not at all common in the Black Lake-Thetford district.

THE JUNCTION AND INTERSECTION OF CHRYSOTILE VEINS.

Under favorable conditions, such as are to be found especially in the producing quarries, the massive rock is traversed by a very complex network of veins, which meet, and also intersect, one another at all angles. Where two veins, inclined at a small angle, meet, they may continue as a single vein. An occurrence of this kind apparently represents either a single fissure which branched at one or more points along its course, or two nearly adjacent but slightly diverging fissures, in which case one may have been formed subsequently to the other as the serpentinization progressed; and from the simple or compound character of the vein below (or above) the forking, it is often possible to decide with some certainty which of these alternatives actually gave rise to any particular occurrence of this nature. Such branching veins may again meet and thus enclose blocks or fragments of massive serpentine. Owing to their nearly parallel courses, there is seldom any disturbance in the direction of the fiber at the point where veins of this type fork.

Where veins meet at wider angles, they usually intersect, each continuing on the other side of the junction with direction and position unchanged; a relatively narrow vein, however, may appear on one side only of such a junction, or it may pinch out after continuing for a short distance on the other side. If one of the veins is appreciably wider than the other, it is the general rule, and from the writer's observations the invariable rule, that the fiber in the wider one is continuous and not at all disturbed by the intersection with the other; it appears to cut across the smaller vein just as cleanly as a younger dyke might cut across an older. With the chrysotile veins, however, it can hardly be doubted that the relative ages of the two are just the reverse of this, and that it is the continuous vein which is the older. The wide veins, which are usually fairly straight and persistent, represent the most prominent fissures, and in many cases the major joint planes, of the peridotite, along which its serpentinization first commenced; many of the narrower ones, on the other hand, are believed to follow cracks which were developed from time to time as the alteration proceeded. That this view of their age relations is the correct one receives confirmation from a closer examination of many such intersections, in which the smaller vein may be seen to penetrate for a greater or lesser distance into the wider one, indicating that, after the main vein had attained a certain width, serpentinization commenced along a fissure intersecting it, and that thereafter the outward growth of the two veins proceeded simultaneously. For the same reason there is often a considerable amount of disturbance and confusion in the direction of the fiber where two veins of approximately the same width intersect.

INCLUSIONS OF MASSIVE SERPENTINE WITHIN THE VEINS.

Fragments of massive serpentine are occasionally seen enclosed entirely within veins of chrysotile, and situated, more often than not, near the central parting. In some cases the relations are such as to leave little doubt as to the correct explanation of the occurrence, since the massive material is clearly a fragment included between two or more branching veins of chrysotile. In other cases, however, the inclusions are more irregular or smaller, and the reason for their presence within the veins is not so self-evident. It seems probable that they are not always to be explained in the same way, and without attempting to exhaust the various possibilities, the two following may be suggested.

The inclusions may in some cases represent the last remains of what was originally a narrow zone of rock lying between two adjacent parallel fissures, where the process of serpentinization was arrested before the outward growth of the fibers from each of the fissures had proceeded sufficiently far to effect a complete coalescence of the two resulting veins, which consequently remain separated here and there by fragments of the still incompletely serpentinized massive rock.

Again, it is possible that the original walls of a fissure might have been intersected by subsidiary cracks to such an extent that the waters, passing along these, have reached the sounder rock beyond, completely surrounding fragments, which were left as islands of partially serpentinized massive rock within the growing vein of cross-fiber; and the same might happen at any similarly fractured zone beyond the original fissure, as the outward progression of complete serpentinization (the chrysotile vein) reached it.